

# Tri-Mode Bandwidth-Tunable Filter Based on Microstrip-to-CPW Resonator

Jian-Quan Huang<sup>1, \*</sup> and Zhi-Han Chen<sup>2</sup>

**Abstract**—A novel microstrip-to-CPW resonator is presented, which can be employed to design bandwidth-tunable bandpass filter. The tri-mode resonator is composed of a dual-mode microstrip resonator and a CPW stub printed on a single piece of substrate. Two varactors embedded in the resonator are utilized to adjust the frequencies of the first and third resonant modes independently, thus flexible bandwidth control can be achieved. For demonstration, a prototypical filter is implemented with fixed center frequency of 1.72 GHz and 9.3%–32.6% fractional bandwidth (FBW) tuning range. Good agreement is obtained between the simulated and experimental results.

## 1. INTRODUCTION

With the rapid development of wireless communication technology, the demand for reconfigurable filters is increasing due to their potential to reduce the circuit size and cost. Microwave reconfigurable filters have been studied for decades, and most of the reported filters focus on the tunability of center frequency [1–3]. In some cases, filters with tunable bandwidth are more desirable than filters with tunable center frequency. However, compared with frequency agility, bandwidth control is much more difficult to be achieved because of the complexity to adjust the inner coupling level.

As research continues, several design methods of bandwidth control have been published [4–6]. In order to obtain controllable inner coupling, a short transmission line and a pair of varactors between resonators were utilized to create controlled magnetic and electric couplings, respectively [4]. In [5], a T-type varactor network between resonators was devised to adjust the coupling coefficient, thus a tunable bandwidth was acquired. Both [4] and [5] use extra controlled coupling network to achieve bandwidth control, which significantly increases the complexity and loss of the filters with more tuning elements. A dual-band bandpass filter was proposed in [6], whose bandwidths can be adjusted by controlling odd- and even-mode resonant frequencies of dual-mode resonators. Nevertheless, most of the tunable filters, such as those mentioned above, only work for narrow-band applications. Studies on wideband tunable filters with controlled bandwidth have less been reported [7].

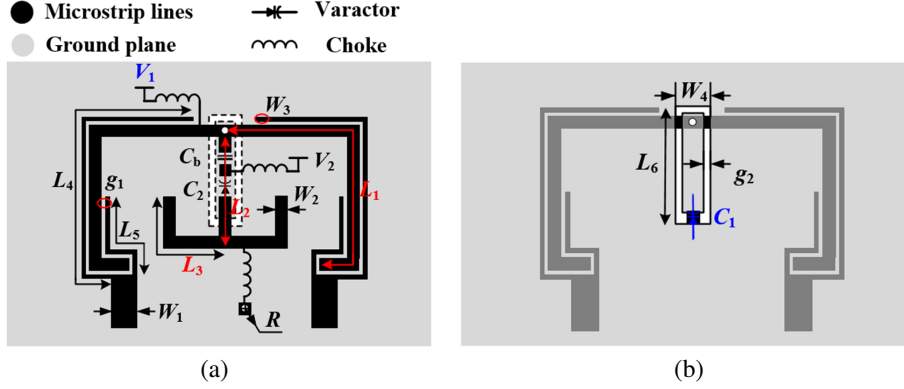
This paper presents a wideband reconfigurable bandpass filter with tunable bandwidth based on a tri-mode microstrip-to-CPW resonator [8]. The resonator consists of a dual-mode resonator on the top layer and a CPW stub occupying the bottom layer. Specially, the first and third resonant modes of this resonator can be tuned individually, which supplies sufficient degree of freedom to adjust both edges of the passband of a tunable bandpass filter. Varactors are utilized to add tuning ability to the bandwidth of the filter. Without increasing circuit size and extra controlled coupling network, low-loss wideband tunable filters with flexible bandwidth control can be implemented with much simpler structures and less tuning components. Finally, the proposed tunable filter is fabricated and measured. Measurement and simulation agree well, which verifies the correctness of the theoretical analysis.

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**Figure 1.** Layouts of the proposed reconfigurable filter. (a) Top view and (b) Bottom view.

## 2. DESIGN OF THE RECONFIGURABLE BANDPASS FILTER WITH TUNABLE BANDWIDTH

Figure 1 depicts the layouts of the proposed reconfigurable bandpass filter. As shown in Figure 1(a), the top layer consists of a modified T-shaped dual-mode resonator and I/O ports. For significantly reducing the size of the filter, the dual-mode resonator is bent, and a T-shaped stub is adopted. The center-tapped stub can not only contribute an additional transmission pole, but also create an extra TZ located at lower stopband. On the bottom layer as depicted in Figure 1(b), a microstrip dual-mode resonator and a CPW stub are connected by a metal via hole to build a tri-mode resonator. Two varactors ( $C_1$  and  $C_2$ ) reversely biased by DC powers  $V_1$  and  $V_2$  are embedded in the CPW and microstrip stubs, respectively. Also, an extra via hole is inevitably introduced to ensure that  $C_2$  works properly. The via hole and resonator are connected by a high-Q chip inductor, which will eliminate the effects of the via hole from the resonator.

### 2.1. Resonance Properties of the Tri-Mode Resonator

Figure 2(a) illustrates the structure of the microstrip-to-CPW resonator, which is equivalent to the microstrip crossed resonator shown in Figure 2(b). Two varactors embedded at both layers of the structure.  $C_1$  connects the CPW stub and the ground, while  $C_2$  is embedded in the microstrip open stub. The proposed resonator is symmetrical, thus even- and odd-mode analysis can be applied to explain the tri-mode resonant characteristics. Then, the odd- and even-mode equivalent circuits are depicted in Figure 3. As shown in the figure,  $Y_1$ ,  $Y_2$ ,  $Y_3$ ,  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  refer to characteristic admittances and electrical lengths for the transmission line sections, respectively. The odd- and even-mode input admittances of the resonator are given by

$$Y_{\text{in\_odd}} = -jY_1 \cot \theta_1 \quad (1)$$

$$Y_{\text{in\_even1}} = jY_1 \tan \theta_1 - \frac{j\omega Y_3 C_1 + Y_3^2 \tan \theta_3}{2 Y_3 - \omega C_1 \tan \theta_3} \quad (2)$$

$$Y_{\text{in\_even2}} = jY_1 \tan \theta_1 + \frac{Y_m Y_v}{Y_m + Y_v} \quad (3)$$

$$Y_m = \frac{j Y_2 Y_3 \tan \theta_2 + Y_2^2 \tan \theta_2}{2 Y_2 - Y_3 \tan^2 \theta_2} \quad (4)$$

$$Y_v = \frac{j\omega C_2 C_b}{C_2 + C_b} \quad (5)$$

where  $C_b$  is the dc block with 51 pF. According to the resonant conditions expressed as follows,

$$Y_{\text{in\_odd}} = 0 \quad (6)$$

$$Y_{\text{in\_even1, in\_even2}} = 0 \quad (7)$$

all three resonant frequencies can be calculated. It is obvious that both even-mode frequencies can be adjusted by  $C_1$  and  $C_2$ , whereas the odd-mode frequency is fixed. This theoretical conclusion can be verified by EM simulation in the case of weak I/O coupling as shown in Figure 4. Figure 4 illustrates that the bandwidth can be changed by  $C_1$  and  $C_2$ , while the center frequency is fixed. By adjusting the capacitance of the varactors, both sidebands can be adjusted independently of each other, which add great flexibility to the bandwidth control.

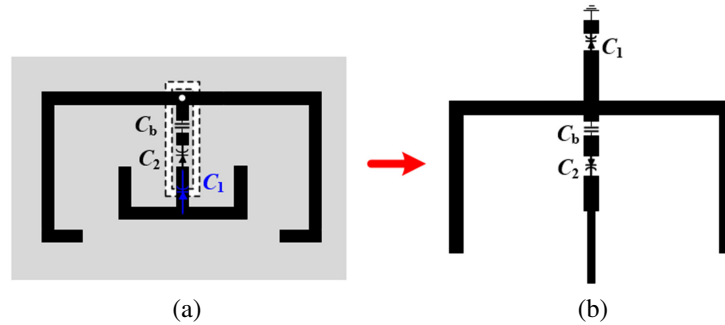


Figure 2. (a) Microstrip-to-CPW resonator. (b) Equivalent microstrip crossed resonator.

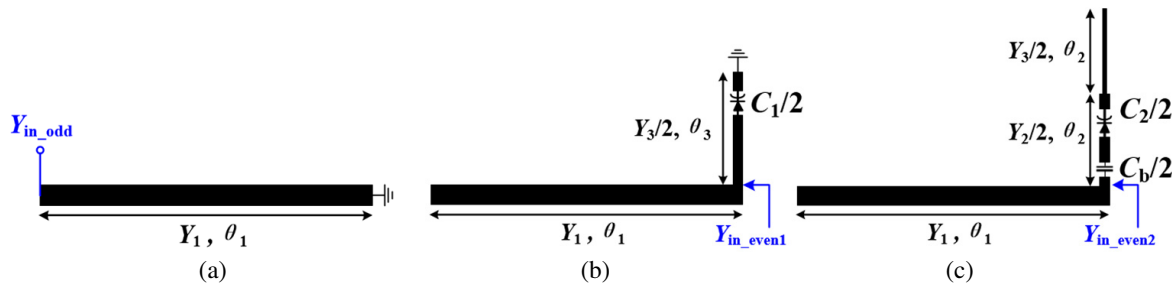


Figure 3. Equivalent circuits of the resonator. (a) Odd-mode circuit. (b) The first even-mode circuit. (c) The second even-mode circuit.

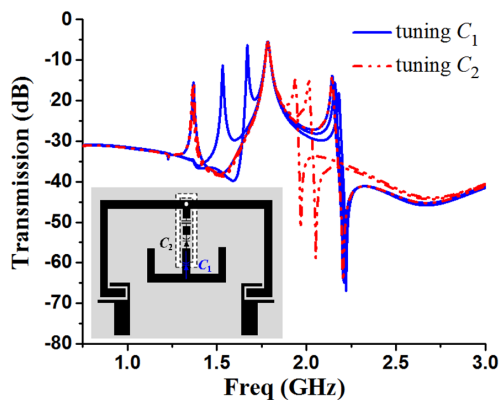


Figure 4. EM Simulations under weak I/O coupling with different  $C_1$  and  $C_2$ .

It is notable that there are two transmission zeros (TZs) located at both sides of the passband, which are introduced by two center-tapped stubs. More importantly, they well adapt to the change of the bandwidth, which enhances the selectivity of the filter.

## 2.2. Design Procedures of the Reconfigurable Filter

On the foundation of the above theoretical analysis, detailed design procedures of the proposed bandpass filter with tunable bandwidth are described as follows:

Step 1) Decide the center frequency of the reconfigurable filter:

In order to simplify designing, odd-mode resonating frequency  $f_{odd}$  is selected as the center frequency. Obviously,  $\theta_1$  is initially set as  $\lambda/4$  at  $f_{odd}$ .

Step 2) Design of the tuning ranges of two even-mode resonating frequencies:

Based on the equivalent circuit analysis,  $\theta_1 + \theta_3$  can be roughly selected as  $\lambda/4$  at the first even-mode resonating frequency  $f_{even1}$ , while  $\theta_1 + 2\theta_2$  should be chosen around  $\lambda/2$  at the second even-mode resonating frequency  $f_{even2}$ .

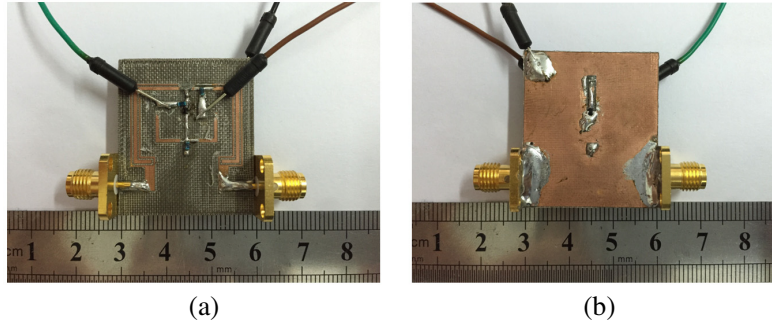
Then, the tuning ranges of two even-mode resonating frequencies can be calculated by using Eqs. (2)–(7). There are five or more degrees of freedom (i.e.,  $Y_1, Y_3, \theta_1, \theta_3, C_1$  for  $f_{even1}$ , and  $Y_1, Y_2, Y_3, \theta_1, \theta_2, C_2$  for  $f_{even2}$ ) to determine the tuning ranges. The admittances and electrical lengths are chosen first, then the changes of even-mode resonating frequencies versus capacitances can be obtained.

Step 3) Trim and optimize the parameters:

The final optimization is performed using EM/circuit cosimulation in Agilent's Advanced Design System (ADS). Some unexpected effects including via-hole effects, losses of lumped elements and radiation of the slots are taken into account when all parameters are finalized.

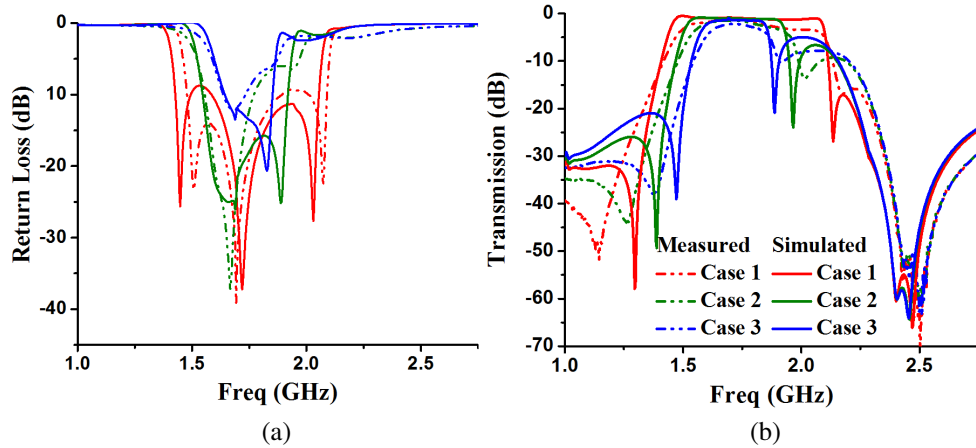
## 3. FILTER IMPLEMENTATION AND RESULTS

In order to prove the validity, the filter is fabricated on a substrate with relative permittivity of 2.55 and thickness of 0.8 mm as shown in Figure 5. All dimensions are determined as follows:  $L_1 = 29.0$ ,  $L_2 = 10.8$ ,  $L_3 = 10.8$ ,  $L_4 = 29.8$ ,  $L_5 = 17.1$ ,  $L_6 = 7.4$ ,  $W_1 = 2.2$ ,  $W_2 = 0.8$ ,  $W_3 = 0.4$ ,  $W_4 = 2.0$ ,  $g_1 = 0.3$ ,  $g_2 = 0.4$ ,  $R = 0.4$  (all in mm). Varactors used in this work are SMV-1413 from SKYWORKS, while the chokes are 100nH high-Q chip inductors of MURATA. The overall size of the fabricated filter is  $0.19\lambda_0 \times 0.14\lambda_0$ .



**Figure 5.** Photos of the fabricated reconfigurable filter. (a) Top view. (b) Bottom view.

Figure 6 depicts the comparisons of simulated and measured  $S$ -parameters of the prototypical filter. All  $S$ -parameters are measured by the Agilent 5230A network analyzer. Figure 6(a) illustrates that lower sideband of the reconfigurable filter has a tuning range of 140 MHz (1.50–1.64 GHz), when  $V_1$  varies from 0.2 to 1.6 V. The upper sideband of the filter, as shown in Figure 6(b), has a tuning range of 260 MHz (1.80–2.06 GHz) when  $V_2$  varies from 0 to 7.1 V. Therefore, the reconfigurable filter reports a 9.3%–32.6% fractional bandwidth (160–560 MHz) at 1.72 GHz. For each tuning state, the insertion loss, including the loss of the SMA connectors, is 1.14–2.18 dB, and the return loss is greater than 10 dB. There are three transmission zeros located at both sides of the passband, as shown in Figure 6(b). The first and second TZs are generated by the microstrip-to-CPW resonator and well adapt to varying center frequency and bandwidth, hence the out-of-band performance of the filter can be markedly enhanced. The third TZ, which is produced by the shorter feed line  $L_5$ , is fixed at 2.43 GHz.



**Figure 6.** Measured and simulated  $S$ -parameters of three cases. Case 1:  $V_1 = 0.2, V_2 = 7.1$ ; Case 2:  $V_1 = 0.8, V_2 = 1.8$ ; Case 3:  $V_1 = 1.6, V_2 = 0$ .

**Table 1.** Comparisons with other reported tunable filters.

| Ref.            | Center Frequency (GHz) | FBW Tuning range (%) | Insertion Loss (dB) | Number of TZs | Number of Tuning Elements* | Size ( $\lambda_g$ ) |
|-----------------|------------------------|----------------------|---------------------|---------------|----------------------------|----------------------|
| [4]             | 1.85                   | 2.2–9.2              | 3.1–6.5             | 2             | 6                          | $0.24 \times 0.25$   |
| [5]             | 1.70                   | 2.9–6.5 (1-dB BW)    | 3.8–4.9             | 2             | 5                          | $0.12 \times 0.07$   |
| [6]             | 1.74 (1st passband)    | 5.8–8.6              | 2.0–4.4             | 1             | 1                          | $0.21 \times 0.21$   |
| [7]             | 2.0                    | 22–34                | 0.8                 | 2             | 6                          | NG                   |
| Proposed Filter | 1.72                   | 9.3–32.6             | 1.1–2.2             | 3             | 2                          | $0.19 \times 0.14$   |

\* Only the tuning elements contributed to tunable bandwidth of the reported tunable filters are considered. NG: not given

Agreement between the simulated and measured results is reasonable. Some errors may be attributed to the fabrication and loss of the lumped components. Finally, Table 1 compares the prototypical filter with several reported bandwidth-tunable filters. The proposed reconfigurable filter has a good bandwidth-tunable performance with a clear and simple design.

#### 4. CONCLUSIONS

In this paper, a concise method of designing bandwidth-tunable filter based on multi-mode resonator is proposed. A double-layer microstrip-to-CPW resonator is analyzed in theory to validate this design method. By tuning the first and third resonating modes of the resonator independently, a reconfigurable bandpass filter with tunable bandwidth is successfully designed, fabricated and tested. Due to the novel microstrip-to-CPW resonator, circuit size of the proposed filter is notably reduced. Measured and simulated results are in good agreement to prove the design concepts.

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